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HIGH ENERGY EFFICIENT SOLID-STATE
LASER SOURCES

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ABSTRACT

Recent progress in the development of highly efficient coherent optical sources is reviewed. This work has focussed on nonlinear frequency conversion of the highly coherent output of the Non-Planar Ring laser Oscillators developed earlier in the program, and includes high efficiency second harmonic generation and the operation of optical parametric oscillators for wavelength diversity and tunability.

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I. Introduction

This final report for NASA Grant NAG 1-182 will describe the progress we have made in the development of highly efficient coherent sources since the last formal report. The thrust of our work in the High Energy Efficient Laser Sources program has moved over the years from high energy laser systems for LIDAR applications to the development of highly efficient diode-laser-pumped solid-state lasers and non-linear optics using these lower power cw sources. This program which began in June 1981 has continued to address specific NASA requirements for laser sources. We describe our recent progress in high efficiency, wavelength diverse coherent sources, including second harmonic generation experiments, a variety of optical parametric oscillator systems, and further laser development.

The specific topics which we have chosen to investigate form a coordinated research program directed to satisfy aspects of laser source requirements for remote sensing applications. Our early research in this program in the area of flashlamp pumped slab lasers has become a basis for the development of high average power diode-laser-array-pumped slabs. Diode pumping offers the potential of high average power operation with good efficiency and long term reliability. Semiconductor-diode-laser pumping of solid-state lasers has been demonstrated in this program to provide the frequency stability and coherence required for Doppler LIDAR wind velocity measurements. Our present investigation of nonlinear frequency conversion can provide the frequency agility required for differential absorption LIDAR measurements of atmospheric water vapor content, pressure, temperature and pollutant concentrations. There are also other important applications of these methods to a variety of applications including coherent communication, fundamental physics, precise timing, ranging, and inertial guidance.

Our current nonlinear frequency conversion investigations are being performed at low power levels but are scalable to the required higher levels. Even with 53 milliwatts of cw 1064-nm laser output, we were able to achieve 56% conversion to second harmonic at 532 nm. We are demonstrating similar levels of conversion in tunable optical parametric oscillation. These recent advances have been made possible by improvements in pump laser technology and the quality of nonlinear optical materials. The nonlinear conversion techniques will be scalable to high average power just as the highly coherent miniature diode-pumped lasers were scaled by injection seeding of high power oscillators or by amplification. High average power nonlinear frequency conversion of neodymium laser radiation can be competitive with titanium-doped-sapphire and Alexandrite lasers, and with further development the nonlinear frequency conversion techniques could offer significant advantages.

II. Review of Recent Progress

A. Harmonic conversion

Our result of November 1987 of 56% conversion efficiency of a 53 mW cw single-axial mode diode-pumped Nd:YAG laser was reported at SPIE's O-E Lase conference[1], the Conference on Lasers and Electro-Optics (CLEO '88) [2] and in the IEEE Journal of Quantum Electronics[3]. The generation of 30 mW of frequency stable cw light at 532 nm has attracted a great deal of attention, and two companies have announced development

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[1] C.D. Nabors, W.J. Kozlovsky, and R.L. Byer, "Efficient second harmonic generation of a diode-pumped cw Nd:YAG laser using and externally resonant cavity," paper 898-18, SPIE O-E Lase '88, Los Angeles, January 11-12, 1988; also published in Proc. SPIE **898**, *Miniature Optics and Lasers* pp. 105-109 (June, 1988).

[2] W.J. Kozlovsky, C.D. Nabors, and R.L. Byer, "52% Efficient Second Harmonic Generation of a cw Diode-Pumped Laser Using a Monolithic External Ring Cavity," paper FE1, 1988 Conference on Lasers and Electro-Optics, Anaheim California, April 1988.

[3] W.J. Kozlovsky, C.D. Nabors, and R.L. Byer, "Efficient second harmonic generation of a diode-laser-pumped cw Nd:YAG laser using monolithic $MgO:LiNbO_3$ external resonant cavities," *IEEE J. Quantum Elec.* **24**, 913 (1988).

efforts to productize our technique. Since then, we have worked to use the $MgO:LiNbO_3$ monolithic resonant frequency doublers to produce higher powers for OPO pumping. We succeeded in operating and servo-locking the resonant doubler while the laser source was driven into deep spiking (see below) to produce peak powers in the green of as much as 500 mW. In this mode, the resonant doubler was also observed to exhibit parametric oscillation at ± 1 nm from the 1064-nm laser light. This phenomenon is still under investigation. We have also begun investigating the use of stoichiometric $LiNbO_3$ prepared by vapor transport equilibration[4] as a material for monolithic harmonic generators and optical parametric oscillators.

B. Singly resonant optical parametric oscillator in $MgO:LiNbO_3$

A monolithic $MgO:LiNbO_3$ singly resonant optical parametric oscillator was operated in both the standing wave and ring geometries[5,6,7]. The OPO was pumped by the second harmonic of the amplified single-mode diode-laser-pumped Nd:YAG laser, operating at a 3-Hz repetition rate. Pump depletions of greater than 60% were observed when pumping four times above the 35-watt threshold, with a corresponding energy conversion efficiency of 35%. The pump power was 120 watts at 532 nm in a 500-nsec pulse.

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[4] Y. S. Luh, M. M. Fejer, R. L. Byer and R. S. Feigelson , "Stoichiometric $LiNbO_3$ single-crystal fibers for nonlinear optical applications," Journal of Crystal Growth **85**, pp. 264-269 (1987).

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[7] W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt and R. L Byer, "Monolithic $MgO:LiNbO_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser," to be published, Optics Letters.

The OPO output at the resonant signal tuned with temperature from 834 nm to 958 nm while the corresponding idler tuned from 1.47 to 1.2 μm. The spectral output varied from pulse to pulse, with single frequency operation observed on approximately 20% of the pulses. The remaining pulses contained as many as eight axial modes of a total spectral width of less than 0.7 cm^{-1}, with a center frequency that was stable to ± 0.2 cm^{-1}. The multimode behavior can be attributed to crystal temperature fluctuations and microscopic mode competition effects during the build-up period of the oscillator. A similar crystal with 2% net output coupling is expected to run single axial mode and have a threshold for singly resonant cw operation of 3 watts.

C. Doubly resonant optical parametric oscillator in $MgO:LiNbO_3$

A doubly resonant monolithic optical parametric oscillator was demonstrated. It was the first OPO ever to be pumped with a diode-pumped solid-state laser as its source. The frequency doubled output of a non-planar ring laser driven into spiking was mode matched into a monolithic cavity much like those used in the harmonic generation experiments. The higher powers were needed as our original OPO design was mis-fabricated in the thin-film coating process, producing an OPO threshold of 40 mW cw rather than the design point of 5 mW. This OPO operated near degeneracy and was temperature tunable from 1.01 to 1.13 μm. Overall energy conversion of the pump light at 532 nm was 7%. This work has been accepted for publication[8].

The OPO could be tuned by applying an electric field across the crystal, which changed the ordinary index of refraction via the electro-optic effect and the effective cavity length via the electro-optic and piezo-electric effects. Near degeneracy the OPO tuned 5 nm

[8] W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt and R. L Byer, "Monolithic $MgO:LiNbO_3$ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser-pumped Nd:YAG laser," to be published, Optics Letters.

with approximately 800 volts applied. Away from degeneracy, the OPO operated in a single axial mode, but tended to drift from mode to mode as the crystal temperature varied, and no active control was used. In October, a new crystal was obtained with improved coatings that oscillated under true cw pumping conditions with a threshold of approximately 10 mW. This OPO is still under investigation.

A complete theory of the tuning and mode control properties of monolithic doubly resonant OPOs is under development, and has been presented at the recent Optical Society of America meeting[9]. This system is also an excellent candidate for the production of squeezed states of light, and an effort is being made to observe these states that exhibit noise levels below that of the Standard Quantum Limit, or the shot noise.

D. Non-planar diode-pumped ring lasers

Theoretical development of non-planar ring oscillators (NPROs) is largely complete, and has been presented at the SPIE's O-E Lase conference and submitted to the IEEE Journal of Quantum Electronics [10,11]. Emphasis has been placed on laser designs with improved isolation to feedback, low threshold, narrow linewidth, and frequency tuning with applied magnetic field.

Support for experimental work has largely been taken over by Stanford University/NASA SUNLITE program (grant NAG 1-839). Currently, the linewidths of

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[9] R. C. Eckardt,C. D. Nabors, W. J. Kozlovsky and R. L. Byer, "Simultaneous Electro-optical and temperature tuning of a doubly resonant optical parametric oscillator," paper TuN4, Annual Meeting of the Optical Society of America, Santa Clara, California, Nov., 1988.

[10] A. C. Nilsson, T.J. Kane, and R. L. Byer, "Monolithic nonplanar ring oscillators: resistance to optical feedback", paper 912-03, Optoelectronics and Laser Applications in Science and Engineering (O-E/LASE'88), Los Angeles, California, January, 1988; also published in Proc. SPIE **912**, *Pulsed Single-Frequency Lasers: Technology and Applications*, pp. 13-18 (June, 1988).

[11] A. Nilsson, E. Gustafson, and R. L. Byer, "Eigenpolarization theory of monolithic nonplanar ring oscillators," submitted to IEEE J. Quantum Electron.

two Nd:GGG ring lasers are being measured by frequency locking to an external reference cavity and spectrum analyzing the heterodyne beatnote between them. This work has yielded a linewidth measurement for the improved oscillators of approximately 300 Hz.

E. Driven relaxation oscillation spiking and noise suppression in diode-pumped ring lasers

Relaxation oscillation noise in diode pumped solid state lasers is a serious problem for many applications such as coherent communications and LIDAR. Relaxation oscillations can be exploited, however, by deliberately modulating the diode laser pump at the relaxation oscillation frequency to produce spikes in the output power whose peak power can be greater than 20 times the cw power at the same average pump power. In the doubly resonant OPO experiment described above, higher intensities were needed to bring the OPO above threshold, so a 10% modulation was applied to the diode pump to induce spiking.

To eliminate relaxation oscillation noise for cw operation, active electronic feedback of the solid-state laser power to the diode laser current was employed to achieve a 25 dB suppression of the noise peak at 375 kHz. This result is of considerable practical importance, and work continues to improve the noise suppression over a broad band. Additionally, a number of effects such as bistability and chaos have been observed for the system and are under investigation.

F. Widely tunable optical parametric oscillator in barium borate

A visible BaB_2O_4 optical parametric oscillator pumped by a single-axial-mode 355-nm source has been demonstrated[12]. This was a collaborative experiment with workers from the University of Hannover. The laser pump souce was a Spectra-Physics DCR-3D

[12] Y. X. Fan, R. C. Eckardt, R. L. Byer, J. Nolting and R. Wallenstein, "A visible BaB2O4 optical parametric oscillator pumped at 355 nm by a single-axial-mode pulsed source," to be published, Applied Physics Letters.

Q-switched unstable resonator Nd:YAG system. The laser was injection seeded for single-axial-mode operation, and the output light spatially filtered before generating the third harmonic, yielding a quasi-Gaussian transverse mode profile. Good coherence and spatial mode quality of the pump is needed for narrow band, stable OPO operation.

An average output power of 140 mW with a signal wave conversion efficiency of 13% an an idler conversion efficiency of 11% for a total conversion efficiency of 24% has been achieved. The observed threshold energy of 2-5 mJ is a factor of 2-3 lower than the value calculated, indicating that previous measurements of the nonlinear coefficient may be low. The oscillator has been continuously tuned from 412 nm to 2.55 μm, limited by the infrared transmission range of the crystal. Through injection seeding we obtained single-axial-mode OPO operation with a corresponding OPO linewidth of less than 3 GHz.

III. Conclusion

This program has been very fruitful, sponsoring in whole or in part the theses of numerous graduate students and leading to a number of publications and 4 patents, including the Monolithic Isolated Single-mode End-pumped Ring laser oscillator (MISER), the angularly multiplexed Nd:YAG laser amplifier, diode-laser pumped Nd:Glass lasers, and highly efficient second harmonic generation in monolithic resonators.

Continued research is focusing on topics of great interest, concentrating on efficient wavelength-diverse coherent sources, and narrow-bandwidth frequency-stable diode-pumped solid-state lasers. The potential to satisfy NASA transmitter requirements for remote sensing and communications applications has clearly been demonstrated. Much of this research, however, was at a preliminary stage.

Further fundamental research directed to improved performance of resonant second harmonic generation and scaling to higher output powers, development of cw OPOs with controllably tuned output, and noise reduction combined with an investigation of squeezed states of light will follow. This work is essential to continued source development.

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16. Abstract

Recent progress in the development of highly efficient coherent optical sources is reviewed. This work has focussed on nonlinear frequency conversion of the highly coherent output of the Non-Planar Ring Laser Oscillators developed earlier in the program, and includes high efficiency second harmonic generation and the operation of optical parametric oscillators for wavelength diversity and tunability.

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